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1. Brief review of the research under the reported grant

The reported research by this principal investigator and his group was done under the AFOSR Grant # F49620-02-1-0097 (JHU #E51-2080), ***Novel laser-based hyper-short pulse sources and single-particle devices***. This grant was activated on February 1, 2002, with the project period of 32 months ending on September 30, 2004, with the no-cost-extention for one year ending on September 30, 2005. The research of this PI and his group has been supported by AFOSR continuously for 25 years by the time of the reported grant. During that period, under AFOSR support, this PI and his group authored or co-authored about 340 publications, among them 12 books and book contributions, 95 regular journal papers, one patent, and 29 conference proceedings; the rest are conference papers.

In particular, under the reported AFOSR support, 21 new papers have been published or submitted for publication (in the bibliography list they are listed as 18 items [1-18], some of which include conference papers as additional part of the reference to the main journal paper; only large invited conference papers are listed separately), This PI is also in the middle of a book preparation [18] (with about 3/4 of the project being ready). The PI and his group continue this resaerch and develop new direction of resaerch under new, current AFOSR grant in pubications part of which is cited here [19-22].

All the effects proposed under the reported AFOSR support are novel and have initiated new opportunities in the fi eld. This PI's and his co-authors' prediction [1] of the avenue to reach ***zepto***-second pulses has been widely cited and heralded as an important discovery by such diverse sources as London "Nature", UPI (United Press international), Physical Review Focus, "Physics World", and many others.

The work by this PI and his group is highly credited by the research community. According to "Science Citation Index" it was cited by other researchers in more than 1700 papers; the total number of citations of his papers is far beyond 3,000. This recognition by the research community is also reflected by the most recent decision of the Optical Society of America (OSA); in October'05, this PI received a Max Born Award of the Optical Society of America, which consists of the plack, medal, and ***$*** 1,500 check. He has been selected for this award for his outstanding contributions to physical optics, in particular for ***"seminal contributions to nonlinear interface and optical bistability effects, hysteretic resonances of a single electron, and physics of sub-femtosecond pulses"***. This award is one of the most prestigious awards of the OSA; it was awarded to 24 researchers for the entire history of the OSA.

The major fi eld of research interests of this PI can be loosely described as extreme nonlinear optics targeting various phenomena and their applications at the edge of capabilities of contemperary science and technology: the interaction of super-powerful lasers (petawatt and beyond) and super-intense laser fi elds (up to $10^{21} - - 10^{23}\ W/cm^2$), with matter; ultra-short pulses (from sub-femtosecond to atto-second to zepto-second EM-pulses); nano-scale phenomena induced by such lasers and pulses (e. g. nano-shock waves in the Coulomb explosion of nano-clusters, resulting in the tiniest tsunami-like waves in physics); generationb of

astrophysics-scale pulse magnetic fi eld up to 10^6 ***tesla***; interaction of relativisticly-intense laser fi eld with relativistic electron beam, in particular large per/pass acceleration of electrons by a laser, anf formation of sub-atto-second down to zepto-second electron bunches, etc.

One of the major fi elds of this PI's reported research (both theoretical and experimental) was the development of new X-ray source for medical applications (bi-chromatic X-ray contrast diagnostics) based on transition radiation generated by MeV electrons in a multilayer solid target. This research in turn is the continuation/extention of the theoretical research on the novel effect of atomic-edges related resonant transition radiation by low- and medium-energy electron beams in multilayer solid-state nano-structures done some while ago [23,24] by this PI and his group under the AFOSR support.

Since the reported AFOSR grant started on February 1, 2002, a number of new results were obtained by this PI and his group in the fi eld of extreme nonlinear optics and nowel radiation sources, in the following directions:

2.i. The discovery of new principle of generating sub-attosecond and zepto-second pulses and ultra-high magnetic fi eld, based on cyclotron-like radiation of a tight, highly-relativistically excited bunch of ionized electrons driven by the standing, circularly-polirized EM-wave of petawatt laser.

2.ii. The prediction of the tiniest tsunami-like shock waves in the Coulomb explosion of nano-scale clusters ionized by high-intensity laser pulse.

2.iii. The pilot proof-of-principal experiment and related theory of medical application of resonant transition radiation in the multilayered structures for Bi-chromatic X-ray contrast diagnostics.

2.iv. Exploration of water-window Cherenkov sources, based on atomic shell resonances, for biological aplications.

2.v. Exploration of the notion of the span of time available to us, nad how far one can go in generating and measuring ever shorter pulses.

2.vi. Prelimanary research on new perspective directions

2. Final technical report on the grant #F49620-02-1-0097 (E51-2080)

2.i. Lasetron: a proposed source of nuclear-time-scale electromagnetic bursts

In our research under this grant we predicted [1-3,5,9,10] a major new phenomenon: nuclear-time-scale, $10^{-21}\ s$, $zepto-second$-long EM bursts can be generated by a Petawatt laser focused on solid particle or thin wire. The system may also generate pulse magnetic fi eld up to $\sim 10^6\ Tesla$.

Recent proposals [25], with one of the major contributions by this PI and his group, explored various avenues to attaining the shortest, $sub-femtosecond$ ($10^{-16}-10^{-17}\ s$), EM pulses of atomic time-scale duration; the train of $\sim 0.25\ fs$ pulses have been observed experimentaly [26]. The further scale of fundamental interest is that of strong nuclear interactions;

since the nuclear energies are beyond $\boldsymbol{1\ MeV}$, the nuclear time scale is in the $\boldsymbol{10^{-21} - 10^{-22}\ s}$ domain (***zepto*** to sub-***zeptosecond***). We demonstrate theoretically that such pulses can be generated using Petawatt lasers, while already widely available Terawatt lasers may generate ***sub – attosecond*** pulses of ~ $\boldsymbol{10^{-19}\ s}$. The pulses will be radiated by ultra-relativistic electrons driven by circularly-polarized high-intensity laser fi elds. They are basically reminiscent to synchrotron radiation; no synchrotron, however, can even come close to running electrons with the energy of $\boldsymbol{50\ MeV}$ at the (laser) frequency $\omega_L \sim \boldsymbol{10^{15} - 10^{16}\ s^{-1}}$ in the $\boldsymbol{0.1\ \mu m}$ radius orbit, as a Petawatt laser can. We call such a system "***lasetron***." It can be achieved by placing a solid particle or a piece of wire of sub-wavelength cross-section in the focal plane of a super-powerful laser. A tight, sub-wavelength cloud of free electrons is formed then by the instant photoioniztion of target within the time much shorter the laser cycle; this cloud is driven by a circularly polirized laser in a λ/π-diameter circle with a speed close to the speed of light, and radiates a very narrow rotating cone of radiation [27] thus producing a hyper-short EM-burst at the point of observation. The Fourier spectrum of the bursts spreads up to the (classical) cutoff $\omega_{max} \sim 3\gamma^3\omega_L$ The major distinct feature here is the forced synchronization of the motion of all radiating electrons by the driving laser fi eld. Radiation of such a synchronized bunch would be viewed by an observer in any point in the rotation plane as huge pulses/bursts of EM fi eld as short as

$$\tau_{pl} \sim 1/(2\omega_L \gamma^3)\ , \tag{2.i.1}$$

where γ is the electron's relativistic factor. With $\lambda_L \equiv 2\pi c/\omega_L \sim \boldsymbol{1\ \mu m}$ and $\gamma \sim \boldsymbol{64}$ (attainable with a Petawatt laser), we have $\tau_{pl} \approx \boldsymbol{10^{-21}\ s}$. In addition to zeptosecond pulses with substantial energy, the magnetic fi eld at the center of rotation may reach ~ $\boldsymbol{10^6}$ ***Tesla*** -- comparable to fi elds in the vicinity of white dwarves. Our results also show that the coherent radiation friction drastically limits the rotation energy of electrons in ultra-intense laser fi elds.

For a model sources ***PL*** - $P_L = \boldsymbol{10^{15}\ W}$ (Petawatt) laser at $\lambda_L = \boldsymbol{1\mu m}$, a close approximation to the LLNL Petawatt laser and a similar system under construction in Japan, we obtain that a single electron would radiate a macroscopic power of $\boldsymbol{180\,W}$ in nuclear time scale bursts, $\tau_{pl} = \boldsymbol{2.6 \times 10^{-22}\ s}$ ($\boldsymbol{0.26\ zs}$). The classical cutoff of the bursts, $\hbar\omega_{cl} \approx \boldsymbol{3\,MeV}$, lies above the energy threshold of some ***photonuclear reactions***, such as neutron photoproduction on Be ($\boldsymbol{1.7\ MeV}$). These numbers indicate the potential of lasetron bursts for time-resolved photonucler physics -- provided that a burst carries suffi cient energy.

To increase the power substantially, one needs to use a tight cloud of electrons with N_e electrons, radiating coherently. Free electrons will then experience an "orbital sander" rotation, moving in phase with the fi eld in identical but shifted circular orbits, their relative positions constant. The resulting radiation will be almost fully coherent, with the radiated power scaling as the particle number squared, $P_{rad} \approx N_e^2\, P_e$, where P_e is the rediation power of a single elctron. Here, however, we have to take into account a new factor - ***coherent*** radiation friction, or back-reaction of radiation. To this end, we approximate a small and dense electron cloud by a ***single pointlike particle*** with the charge $q = N_e\, e$ and mass $m = N_e\, m_e$, which we will call a "***fat electron***". Our claculations show that the relativistic factor γ is then:

$$\gamma = \sqrt{1 + \varepsilon_L^2/(1 + \Gamma_{fat}^2)}\,. \tag{2.i.2}$$

where $\Gamma_{fat} \equiv N_e\,\gamma^3\Gamma_e$, is the radiation damping constant of fat electron, with $\Gamma_e = (4\pi/3)(r_e/\lambda_L)$ being such a constant for a single nonrelativistic electron, and r_e an EM-radius of an electron. Here also $\varepsilon_L \equiv E_L/E_{rel}$, where E_L is the laser field, and $E_{rel}(\omega_L) = m_e\omega_L c/e$ is a relativistic scale of the field strength. The full energy of radiation is then

$$P_{rad} = N_e^2\Gamma_e m_e c^2\gamma^2(\gamma^2 - 1)/2\pi \tag{2.i.3}$$

The further increase of γ is drastically inhibited as the laser intensity ε_L^2 increases. This still allows for spectacular output. For example, if the number of electrons in the target is such that, for $\varepsilon_L = 100$ (PL), we need $\gamma \approx (2/3)\,\varepsilon_L$, then $N_e \approx 300$, and one may expect EM-bursts of $0.9\,zs$, separated by $3\ fs$ intervals, each burst carrying $3\ fJ$ energy with the spectral cutoff at $1.2\,MeV$. If we increase N_e to 21,000, the energy/burst grows to $5\ pJ$, but γ drops to $(1/4)\,\varepsilon_L$, so that $\tau_{pl} \sim 17\ zs$, which is still very short.

A ***thin wire*** positioned in the laser focal plane normally to the laser beam propagation could be an even more promising target. Because of the coherence, the wire antenna will radiate only twice per each cicle, with the radiation highly concentrated in ***two very narrow beams*** strictly normal to the wire and almost normal to the laser beam. The angular collimation of the radiation by such a 3D antenna due to the laser beam of the size $w_L \gg \lambda/2\pi$ will mostly be concentrated within the angle $\Delta\psi_{min} \sim (\lambda_L/2\pi w_L)\cdot\varepsilon_{max}^{-3}$. This will result in great enhancement of radiation intensity in far field area, and may also be of key importance for future experiments: the pulses appearing only in two well defined opposite direction and separated in time by half the laser cycle, would be a clear signature of the lasetron effect.

The driven motion of ionized electron cloud, which will largely maintain its initial small size for a large number of laser cycles, will create a strong magnetic (M) field normal to the rotation plane. We estimate the highest possible M-field in the lasetron as:

$$B_{max} \sim e\,n_e\,\lambda_L/12 = \pi/6\cdot(\lambda_L/\lambda_C)\cdot(n_e\cdot a_0^3)\cdot B_0 \tag{2.i.4}$$

where n_e is the density of the cloud, $B_0 = e\alpha/a_0^2 \sim 1.33\times 10^5\ G$ is the "Bohr" M-field scale, $a_0 \approx 0.53$ Å, is Bohr radius and λ_C is the Compton wavelength. Choosing a high-Z electron-rich material we have $B_{max} \sim 4\times 10^9\ G$ for $\lambda_L \sim 1\ \mu m$, and $\sim 4\times 10^{10}\ G$ for $\lambda_L \sim 10\ \mu m$. The field will be oriented parallel to the laser propagation direction, and has the transverse size $\sim 2\rho \sim \lambda_L/\pi$; its duration will be about the same as that of the originating laser pulse.

It has to be noted that our first paper [1] on the subject has triggered a lively discussion on the coherent nature of the pulses radiated by a tight bunch of electrons, which prompted us to elaborate [2,3] on the profound difference between synchrotron radiation and the radiation of highly coherent laser-driven bunches.

Concluding this section, we have demonstrated theoretically the feasibility of a system (lasetron) capable of generating EM bursts of large energy on a nuclear time scale ($10^{-21} - 10^{-22}\ s$) using Petawatt lasers. It is also capable of generating superstrong magnetic

pulse field on astrophysical scale up to ~ 10^{10} G.

2.ii. Shock-shells in Coulomb explosion: nano-tsunami

While following-up our previous research under this AFOSR grant on ultar-short pulses, see previous Section, and expanding our exploration into the physics of nano-clusters irradiated by a powerful laser, we discovered [4,12] that not only the motion of free electrons (due to photo-ionization) can be a very promissing source or radiation, but the remaining core of ions in the cluster can exhibit a completeley unexpected at the moment new phenomenon: the tiniest, nano-scale tsunami-like shock wave during its so called Coulomb explosion.

When a cluster, a nano-corpuscule comprising of tens to thousands of atoms or molecules [28], is irradiated by a powerful laser, it becomes very rapidly and highly ionized [29-31]. The ionized electrons are almost instantly swept away by laser. A remaining heavy ion core is then torn apart by repulsing Coulomb forces triggering the so called Coulomb explosion (CE). While CE of clusters is well explored by now, the possibility of a strikingly dramatic and universal phenomenon in it has apparently been overlooked. We demonstrated [4] that if the outer layer of ions is less dense then the center -- a typical situation -- the CE must generate a spherical shock at its leading edge. It is formed by inner layers over-running the outer ones, which is reminiscent of the tsunami formation. Usually, there is also an "anti-shock" at the trailing edge, moving slower. This results in an expanding double-edged shock-shell, which eventually encompasses almost entire ionic cloud. These effects make the first known shock phenomenon at the nano-level, with the ramifications from quasi-2D dynamic crystal formation to high-probability nuclear reactions ***inside*** the cluster. The CE shocks should appear also in carbon nano-tubes and metal thin wires, where it engages up to billions of ions.

In the theoretical work on CE, [32,33] it has usually been assumed that the ion core is a sphere of ***homogeneous*** density of ions (a ***uniform*** model), albeit it is known that the density decreases at the periphery. Initially uniform, the density remains uniform (and discontinuous) during CE, see below. We show this result does not hold even for slight non-uniformity; if the outer layers are less dense than the core center, a drastic change of CE behavior occurs. In such a case there always are inner ions moving ***faster***, than outer ones and displaying a typical shock pattern succinctly encrypted in the old prophesy, ***"He who cometh after me is mightier than I am"***. Those faster ions will eventually run over most of the other ions preceding them. Ions that started out at different points, come together at a certain critical point. Their density at that point becomes infinite, thus forming a ***leading – edge*** shock.

Let us still assume that the cluster is a sphere filled by identical ions, but the initial ion density, $D(r_0)$, has a profile, sloping down to the periphery, so that $D(r_0) = (4\pi r_0^2)^{-1} dN(r_0)/dr_0$, with $N(r_0)$ being the total number of ions within a sphere of a radius r_0, is a decreasing function of r_0. The acceleration of an ion at the point $r(t)$ is

$$d^2 r/dt^2 = (en_i)^2 N(r)/Mr^2 \tag{2.ii.1}$$

where n_i is the degree of ionization, e is the electron charge, and M is the ion mass, (Note that

for a uniform density profile, $d^2r/dt^2 \propto r$.) So long as each small element of the expanding cloud comprises of ions of the same momentum, the total number of ions enveloped by the sphere of radius r, remains unchanged, i. e. $N[r(r_0)] = const = N(r_0)$, where $r(r_0)$ is a trajectory of an ion with $r_{t=0} = r_0$. Essentially, this is a condition that no two (or more) trajectories cross their paths; it will be violated at some point of time, which marks the formation of a shock.

For dimensionless variables, $\tau = t/t_0$, $s_0 = r_0/R_0$, $S = r/R_0$, $Q(s_0) = N(s_0)/N_\Sigma$, $\rho(S) = D(r)R_0^3/N_\Sigma = (4\pi S^2)^{-1} dQ(S)/dS$, where R_0 is a radius scale of a cluster, N_Σ is the total number of ions in cluster, and $t_0 = (en_i)^{-1}\sqrt{MR_0^3/N_\Sigma} = (en_i)^{-1}\sqrt{3M/4\pi\bar{D}}$ [34], with $\bar{D} = 3N_\Sigma/4\pi R_0^3$ being a "mean" initial ion density, Eq. (2.ii.1) is now written as

$$d^2S/d\tau^2 = Q(s_0)/S^2 \qquad (\ Q(\infty) = 1\ ) \tag{2.ii.2}$$

If CE starts out with all ions at rest, the first integral of this equation, the conservation of energy, is $(dS/d\tau)^2 = 2Q(s_0)\cdot(s_0^{-1} - S^{-1})$, and the trajectory $S(\tau)$ of an ion is as:

$$\sqrt{x(x-1)} + \ln(\sqrt{x} + \sqrt{x-1}) = \tau\sqrt{2Q(s_0)/s_0^3}, \quad with \quad x = S/s_0\ , \tag{2.ii.3}$$

For the uniform model, $Q(s_0)/s_0^3 = 1$ for $s_0 \le 1$ the cloud stays uniform, since for any $s_0 \le 1$, the ratio S/s_0 is S-independent. The cloud radius is then $S_{cl} \approx 1 + \tau^2/2$ for $\tau \ll 1$, and $\approx \tau\sqrt{2}$ for $\tau \gg 1$. However, if the initial density profile $\rho(s_0)$ zeroes out smoothly, Eq. (2.ii.3) displays a dramatic switch of system behavior. Let us consider as an example smooth initial profiles

$$Q(s_0) = s_0^3/(1 + s_0^{3\mu})^{1/\mu}\ ; \quad and \quad \rho(s_0) = (3/4\pi)/(1 + s_0^{3\mu})^{(1/\mu)+1}\ ; \tag{2.ii.4}$$

with a control parameter, $\mu = const > 1/3$, allowing one to handle profiles from smooth at $\mu \approx 1/3$ to uniform but discontinious at $\mu \to \infty$. For $\mu \gg 1$, the "transition" depth is as $\Delta s_{tr} \sim (4/3)\mu^{-1}$. At $\tau = 0$, the ion acceleration peaks inside the cloud, where ions move faster than the rest of the bunch. This translates into the velocity profiles $v(S)$ peaking in the inner area too, as time increase. These profiles tell the whole story, with the peak of $v(S)$ being the shock ***predictor***. As inner ions rush out faster than the outer ones, at a critical moment, τ_{cr}, both of these groups end up at the same location, S_{cr}, which marks the ***breaking***, or critical point of a shock, where $\partial s_0/\partial S = \partial^2 s_0/\partial S^2 = \infty$, or $\partial v/\partial S = \partial^2 v/\partial S^2 = \infty$. Since $\rho(S) \propto \partial s_0/\partial S$, the density $\rho(S_{cr}) \to \infty$, too. For $\mu = 1$, $\tau_{cr} \approx 3.8$ and $S_{cr} \approx 3.3$. From this moment on, with the fast inner ions rushing outward, and the slower outer ions falling behind, the function $v(S)$, should assume multi-valued, or hysteretic-like shape. Thus, in a certain area of the cloud, at each of its point there will be now groups of ions with different velocities. This also implies that the charge Q in (2.ii.2) that acts to accelerate ions at the point S, is not a function of a single originating location s_0 anymore, which makes Eq. (2.ii.3) invalid. Instead, beyond the critical point, $Q(S)$ is numerically evaluated as a total sum/integral of all the ions enveloped by a sphere of radius $S(\tau)$, regardless of their origin and current velocities. The "knees" of the function $v(S)$, i. e. the points S_{sh}, at which $dv/dS = \infty$, correspond to infinite density, $\rho = \infty$; these are ***shock edges***. Near the critical point, S_{cr}, the pole of density function is as $\rho \propto |S - S_{cr}|^{-2/3}$, while the poles near the shock edges are as $\rho \propto |S - S_{sh}|^{-1/2}$. The fastest

moving ions of the "advanced" knee form a ***leading edge*** shock, while the most falling-behind ions form a ***trailing edge***, or "anti-shock". Both these edges together make a shock-shell, which widens with time and finely encompasses almost entire cloud.

The shock phenomenon is universally inherent to any initial density profile with "sloping down" non-uniformity, regardless of the specific model or the spatial depth of transient layer. However, certain details are model-specific. While "smooth" models like (2.ii.4) always produce double-edged shell, the relative density in both edges may change. For example, for the "***tanh***" model, $Q(s_0) = [\tanh(s_0^{3\mu})]^{1/\mu}$ or $super-Gaussian$ model, $\rho(s_0) = (3/4\pi)\exp(-s_0^{2\mu})$, the intensity of the trailing edge quickly diminishes as μ increases. Furthermore, in a "cut-off" model: $\rho(s_0) = (3/4\pi)\cdot[1-(s_0/s_{cut})^{\mu}]$ if $s_0 < s_{cut}$, and $\rho(s_0) = 0$ otherwise, where $s_{cut} = (1+3/\mu)^{1/3}$, the trailing edge disappears, being replaced by the discontinuity of the gradient of density, $d\rho/dS$. The velocity profile here has only ***two*** branches. In fact, the initial profiles $\rho(s_0)$ can be constructed, that would generate ***multiple*** number (i. e. >3) of solutions in the hysteretic-like area. Although of certain mathematical interest, they most likely may not be of substantial significance in real clusters. The exceptions could be "compound" clusters consisting of different ionic species, e. g. hetero-nuclear molecular clusters or "engineered" clusters formed by depositing layers of atoms upon a cluster initially made of different atoms. However the shock phenomenon is well pronounced for all of them.

A common feature of the CE behavior for any model in the area ***below the shock-shell*** at sufficiently large time, is that the velocity is proportional to the distance S, while the density $\rho(S)$ is becoming flat. These are, essentially, features of the uniform model; at that area and $\tau \gg 1$, we have $dS/d\tau \approx S/\tau$, and $\rho \approx \rho_{\tau=0} / (\tau\sqrt{2})^3$, where $\rho_{\tau=0} = 3/4\pi$. When a profile approaches the ***uniform*** one ($\mu \to \infty$), the width of a shock shell in smooth models or the double-solution area in a cut-off model, is narrowing as expected. Amazingly, however, neither the critical point of the shock formation moves infinitesimally close to the edge of the cluster, $S \approx 1$, nor critical time tends to zero! Instead, these parameters are ***finite***, $S-1 \approx 0.635$ and $\tau \approx 1.237$ respectively. These numbers are universal, independent on model, and are roots of equations: $\sqrt{S(S-1)} + \ln(\sqrt{S}+\sqrt{S-1}) = 2S^{3/2}/3\sqrt{S-1}\ (=\tau\sqrt{2})$; so, even a slight perturbation of a uniform model results in a shock with non-vanishing formation parameters.

So far we assumed that all ions are initially at rest. Will the initial non-zero velocities be able to suppress the shock? For an arbitrary initial velocity profile, $v_0(s_0)$, the conservation of energy reads as: $(dS/d\tau)^2 = 2Q(s_0)\cdot(s_0^{-1} - S^{-1}) + v_0^2(s_0)$. Let us assume the worst-case scenario with "Big Bang" connotations, whereby $v_0(s_0) = H_{ce}s_0$, where H_{ce} is a "nano-Hubble" constant. Calculations show that if H_{ce} is higher than some critical value, $H_{ce} > H_{cr}$, the shocks will be suppressed; e. g. for the profile (2.ii.4) with $\mu = 1$, we have $H_{cr} \sim 0.22$. However, we found that H_{cr} increases rapidly as the transition depth Δs_{cr} decreases; in most of the cases of interest, the initial thermal velocity of ions would be insufficient to suppress the shock.

The CE shock is not limited to spherical clusters. Calculations show that ***all the results*** hold true for a cylindrical geometry. This tremendously broadens the scope of conditions and

systems to observe and use this phenomenon. For example, instead of clusters, one can use much better defined and designable ***carbon nano-tubes***, or well engineerable wires of ***nm***- to μm diameter (similar to the ones proposed by us for a ***lasetron*** source [1]), that would produce a huge amount of ions injected into CE and shock when irradiated by laser. A gold wire of $20\ nm$ diameter positioned normally to the laser beam in the focal spot of ~ $5\ \mu m$ size, would inject ~ 2×10^9 ions with the huge total charge up to $10^{10} - 10^{11}\ |e|$. The shocks could also be generated on larger scales of ion energy (MeV instead of KeV), as a laser pulse expels almost all the electrons from the cluster of heavy ions.

The CE shocks can manifest themselves through or can be used for quite a few physical effects. The formation of infinitesimally thin shock edges amounts to the 2D spherical surface within which the ions may form a dynamic yet well organized structure akin to a 2D crystal with a near-space ordering. This "shock crystal", and in general, the shock edges could be detected and studied via scattering of electron or X-ray beams off the CE and observing their angular spectra. One of the most rapidly growing research fields related to laser-irradiated clusters and ensuing CE [32,33], as well as in other nano-structures [35], is the nuclear reactions, in particular, the production of neutrons due to collisions of sufficiently high energy ions in deuterium. Thus, another, and perhaps most spectacular, effects due to CE shock, could be that these reactions may occur ***mostly*** inside the cluster due to collisions between the ions of the ***same*** cluster, e. g. fast ions at the leading edge and slow-moving ions of the lower branch of velocity curves. The number of reaction-generating collisions per "hot" ion inside a cluster, n_{cl}, as compared to that of outside it, i. e. in almost homogeneous plasma, n_{pl} is $n_{cl}/n_{pl} \sim O(1)\times \rho_{cl}/\rho_{pl}$, where ρ_{cl} and ρ_{pl} are number densities of ions in a cluster and in plasma respectively. The resulting enhancement for such a mechanism compared to conventionally expected plasma collisions is a few orders of magnitude, which is consistent with most recent experimental data [33]. This effect may also be instrumental in detection and verification of CE shock: the neutron burst ***during the relatively short period*** of Coulomb explosion could be a shock signature.

In fact, the CE shocks studied here is easily related to a broader and bigger physicsl picture. Any explosion, regardless of the nature of forces that set it in motion, be it Coulomb, thermal, nuclear, or Super-Nova and other stellar or galactic explosions [36], is prone to generating shocks; it is more expected of shocks to occur in explosion than not. The defining factor here is that due to non-uniformity of initial conditions, the velocity profile at some moment has a peak inside the explosion cloud, which makes it in essence the shock predictor. In view of that, it is amazing that shocks have not showed up in the Big Bang model of the Universe. The initial (and ensuing) uniform profile in CE is an analogy to the uniform Hubble expansion in the Big Bang model. Any perturbation of that idealized profile should have brought about a "Big-Shock", whose primordial remnants might still be found in the Universe. Example is a possible existence of a matter that expands slower than it is predicted by the Hubble constant, and furthermore, that is seen as running ***toward*** us, similarly to the slow front tail of CE velocity profile seen by the fast emerging ions. Another connection can be found at the opposite, sub-nucleus scale, where a shock can be expected in the expanding quark plasma [37]; the required condition here would be that the critical time of shock formation be shorter than that of plasma

hadronization.

In conclusion, we found that rapid photoionization and ensuing Coulomb explosion of clusters can lead to the shocks formation due to the hysteretic-like velocity profi les produced by the non-uniformity of initial conditions. This phenomenon may result in many effects, in particular, fast collisions of ions with different velocities and ensuing nuclear reactions inside the explosion cloud.

Last minute note: in a paper [33] published in PRL, it was demonstarted by using massive computer simulations that the shock-shells predicted by us analytically [4] for fully ionized clusters, hold for much broader and general conditions in large deiterium clusters, which creates greatly favorable conditions for their experimental observation and possible observation of ***in-claster*** fusion nuclear reactions. Our work [4] was given a full credit for the prediction; that work has also been cited and used in many recent publications by other authors; e. g. in the latest work [34] in applications to shock waves in cold plasma.

2.iii. Transition radiation as an X-ray source for medical applications: proof-of-principle experiment

In the last year of the reported grant, we (Dr. Peter Shkolnikov, PI, at the Center for Advanced Sensor Technologies Stony Brook University, Stony Brook, NY 11794, and this PI), have started a new research, **Transition radiation generated by MeV electrons in a multilayer solid target as an X-ray source for medical applications: proof-of-principle experiment**. The contribution of this PI and his group was arranged ***via*** an Addendum to the reported grant under this PI, and was aimed to provide a theoretical/design/computational/data-processing support for the experimental research by the group of Dr. Peter Shkolnikov, PI, at the Center for Advanced Sensor Technologies Stony Brook University, Stony Brook, NY 11794. The entire research effort is aimed at the experimental verifi cation of pioneering theoretical results of this PI's group (including Dr. Shkolnikov), on X-ray transition radiation generated by MeV electrons in multilayer solid targets, which, if successful, will become a basis for a practical, low-cost X-ray source, in particular for medical applications. It is continuation/extention of the theoretical research on the novel effect of atomic-edges related resonant transition radiation done some while ago [24] by this PI and his group under the AFOSR support. At the moment, both experimental and theoretical effort on that project are in the progress; the most recent publication (in print) is to appear [21].

So far, experimental observations and proposed applications of X-ray transition radiation relied solely on high-energy (a few GeV) electron beams, The results of this PI's group predicted, in particular, that multilayer structures irradiated by electrons with moderate (1-10 MeV) electrons may become a practical, low-cost source of X-rays for numerous applications. The reported research was aimed at the following specifi c objectives: (1) To prove that the transition radiation can be achieved with a solid-solid interface; (2) To prove that the dielectric constants at atomic absorption edges, fi rst predicted in [24], can be a powerful mechanism of radiation; (3) To prove that a solid-state multilayer structure can be a source of coherent transition radiation; (s To develop and verify a quantitative theoretical model for future applications.

The proof-of-principle experiment at the center of the proposed effort is in the progress at SUNY Stony Brook; it went through the stage of the fi rst design, and choice of accelerator. The choice of material (we switched from the initially-proposed $Mo + Si$ pair to $Mo + Ag$ pair for the reasons explained in the details in the next Section 3) and design parameters for the structure (thickness of the layers and of the entire structure) has been done by this PI and his group. This PI and his group provide a theoretical support for the experimental effort; the support includes design computations, statistical estimates of the radiation in periodic structures with slight randomization, predication of the X-ray radiation output, participating in the experimental data processing, interpretation of the results, and developing the physical and mathematical model for future research & development aimed to develop new multi-layer structures with the elements needed for the X-ray tomography for the wavelengths near the K-shell transitions of Iodine and Gadolinium for specifi c medical applications.

Bi-chromatic X-ray contrast diagnostics, proposed two decades ago [40], was developed into a useful medical tool [41]. The diagnostic utilizes a large difference in absorption of X-ray photons with energies just below and just above the contract material (Iodine). Despite apparent success, the technology has not become widespread, in large part because it relied on a synchrotron radiation available only at major national facilities like Light Sources at BNL or LBL. Recently, R&D has started on using X-ray transition radiation for that purpose [42]; however, while a number of advances have been made, the technology still relies on a GeV electron accelerator.

The reported research was based on the earlier work of this PI's group [24] supported by AFOSR, which have theoretically demonstrated feasibility of generating intense X-ray transition radiation by few-MeV electrons traversing solid multilayer structures. The most dramatic difference of those results from the main body of work on X-ray transition radiation is the possibility to use electron beams of 5-10 MeV energy to generate X-rays in 30-50 keV range, whereas the conventional technology based on foil stacks needs electron energy three orders of magnitude higher. As a result, widely available and relatively inexpensive industrial electron accelerators may be used instead of electron synchrotrons of the national-facility kind. Another major innovation is the utilization of resonances at inner-shell absorption edges of materials to narrow the bandwidth of the generated radiation and greatly enhance the intensity of the transition radiation at each interface due to huge contrast of dielectric constants of the adjacent layers based on the gigantic jumps of absorption in the spectral vicinity of the inner-shell absorption edges. This research aimed at providing experimental verifi cation of this theoretical concept, makes an important step toward practical applications.

Our prior theoretical results, to be adjusted to new materials and wavelengths, indicate that one may expect $10\ MeV$ electron/30 keV X-ray photon conversion effi ciency in the proposed process at $\sim 10^{-4}$. Experiments with iodine contrast have shown that 10^9 photons in $0.2\ s$ are suffi cient for applications. The selection of materials for the multilayer structure is determined by the desirable application. For the proof-of-principle experiment proposed here, however, we started from $Mo - Si$ multilayers, which are well-researched and made to order as EUV mirrors. However, during our detailed calculations during last year, we realized that our

original approach in [24] based on choosing the layer of heavy atoms as "radiator" with a chosen $\boldsymbol{K}$-shell transition, and the layer of light atoms as a neutral "spacer", which was the right thing to do in the soft X-ray domain, does not produce desirable results. The major drawback was that in the $\boldsymbol{20 - - 50\ KeV}$ X-ray domain the transition radiation spectrum with such pairs shows a spectral ***dip*** at the chosen $\boldsymbol{K}$-shell, instead of spectral ***peak*** (see details in the Section 3, "Proposed Research"). While this effect may be beneficial for certain applications, in our case it proved to be counter-productive.

The problem arose how to break through this obstacle by perhaps finding new approach to the proper choice of the pairs of "radiator" and "spacer". Our diligent search through almost 70% of the elements in periodical table and through huge spectral date for each one of them, resulted in locating at few candidates of spacers for any given "radiator" (of which we have not much of choice) to produce strongly pronounced resonant peak of transition radiation with the contrast better than two orders of magnitude (see details in the Section 3, "Proposed Research"). Surprisingly enough, these new spacer candidates as a rule are ***heavier*** than the radiator. One of criteria/stipulations on these candidates is that they have to be technologically viable and accessible, which narrows down the field of candidates, but still leaves at lest two candidates for each radiator element. For our reported proof-of-principle experiment our choice was $\boldsymbol{Mo}$ for radiator (~ $\boldsymbol{20\ KeV}$), and $\boldsymbol{Ag}$ for spacer.

For envisioned medical applications of RTR, a few $\boldsymbol{MeV}$ electron beams are required, and the expected radiation is in the hard-X-ray domain (typically, a few tens of $\boldsymbol{KeV}$'s), the thickness of each element, or "period" (which is a combination of two layers) is to be around $\boldsymbol{100}$ Å. For the specific example of $\boldsymbol{Mo}$ (molybdenum) near its main $\boldsymbol{K}$-shell transition (atomic absorption edge) at $\boldsymbol{20\ KeV}$, which corresponds to the wavelength of $\lambda \sim \boldsymbol{0.62}$ Å. The spacing $\boldsymbol{l_0}$ between the adjacent periods of multi-layer structure: is determined as $\boldsymbol{l_0} \approx \boldsymbol{2}\,\lambda/(\gamma^{-2}+\theta^{2})$, where θ is the angle of transition radiation at the wavelength λ, and $\gamma = \boldsymbol{E/mc^2}$ is the relativistic factor of electrons. The optimum condition [24] corresponds to $\theta = \boldsymbol{1}/\gamma$, so that the above equation yields a simplified formula for the optimal thickness of one individual period of the structure:

$$\boldsymbol{l_0} \approx \lambda \times \gamma^{2} \qquad (2.iii.1)$$

whereas the total X-radiation intensity in the direction of the resonant angle θ at the resonant wavelength λ is proportional to the square of the contrast of dielectric constants of adjacent layers at λ, and the square of number of the layer pairs, $\boldsymbol{N}$. This is valid only for the idealized conditions of ideally sized thicknesses of the layers (i. e. ideal coherence of radiation), the absence of photo-absorption and electron scattering, etc. While the two latter factors have been discussed in detail in our work [24], the de-coherence introduced by inevitable random variation of the spacing between the layers due to fabrication conditions, remained open question, which has to be resolved immediately in order to formulate the tolerance requirements needed for fabrication specs.

For the energy of electron beam $\sim \boldsymbol{10\ MeV}$, $\gamma \approx \boldsymbol{20}$, so that we have $\boldsymbol{l_0} \approx \lambda \times \boldsymbol{400} \approx \boldsymbol{248}$ Å. After a long search, we decided that for the reported experiment we have to use the most accessible accelerator, the Accelerator Test Facility (ATF) at Brookhaven National Lab. Its energies ($\boldsymbol{25 -- 75\ MeV}$) are higher than we initially planned to use, but still within the limits of our proposal, so decided to use the lowest energy available on ATF, $\boldsymbol{25\ MeV}$, and thus $\boldsymbol{l_0} \approx \lambda \times \boldsymbol{2,500} \sim \boldsymbol{1,550}$ Å. Technologically, such structures are available. In the process of preparation, though, Shkolnikov's group found that the technology needed to manufacture the real multi-layer target is too complicated for their own deposition equipment, so that they will order it from an outside supplier, when they are reasonable certain that the setup works. A question important for the experiment and potential applications arose immediately: what is the tolerance in the thicknesses $\boldsymbol{l_0}$ of each individual period to utilize the coherence gain from using relatively large stack of these layers? What is the number of layers to utilize the available dispersion of the spacing between the layers?

We addressed this question last year; the results of detailed theory developed by us, have made the basis of our most recent paper, [7], with the emphasis of X-ray transition radiation, that has just been just published. In that paper, we derived a simple analytical formula in the case of Gaussian probability distribution of their period. Using Monte-Carlo simulations, we also demonstrated that many other distributions, some of them drastically different from the Gaussian, show the statistical properties closely coinciding with it. We also found a simplified heuristic that fits all of these results with very reasonable precision.

The simplest way to quantify the coherence of the multi-element structure is to look into the intensity of the signal from these system in the far-field area. If the total number of elements is $\boldsymbol{M}$, and they are ideally equidistant, the ideal ***coherency gain***, $\boldsymbol{G}$, of the intensity of radiation in the maximum of the main lobe (e. g. first maximum in the diffraction grating) ***compared to that from a single element*** is $\boldsymbol{G_{coh}(M) = M^2}$, due to ***the fully constructive interference*** for the right conditions in the far-field area, the ***amplitude*** of the radiation is the ***sum*** of all the individual amplitudes, i. e. proportional to $\boldsymbol{M}$, and therefore the total intensity is proportional to $\boldsymbol{M^2}$. In the opposite case of randomly positioned elements, the expected gain is simply $\boldsymbol{G_{rand}(M) = M}$, since now only the ***intensities*** add up. In the general case of intermediate coherency, one can introduce the ***coherency enhancement***, $\boldsymbol{\mathcal{E}(M) \equiv G(M)/M}$, and using a ***coherency range*** $\boldsymbol{N_{coh}}$, determined by the normalized standard deviation of of the layer period, $\sigma_0 = \sigma_l \,/\, \boldsymbol{l_0}$, obtain ***exact*** formula for the Gaussian distribution of the spacings between the elements, and compare it with other statistical models of the distribution function of the spacings, in which case one needs to use Monte-Carlo method to calculate $\boldsymbol{\mathcal{E}(M)}$. We have shown that for any parameters of practical importance, the results fro many, even drastically different statistical models of the distribution function show very close results for $\boldsymbol{\mathcal{E}(M)}$, which is basically due to the central limiting theorem of the probability theory. We also were able to find a heuristic simplified analytical formula for the coherency enhancement:

$$\boldsymbol{\mathcal{E}(M) \equiv \frac{G(M)}{M} \approx \frac{M \cdot N_{coh}}{M + N_{coh} - 1}}\,, \qquad \boldsymbol{with} \qquad \boldsymbol{N_{coh} = \frac{1}{(\pi\, \sigma_0)^2}} \qquad (2.iii.2)$$

For the future applications, assuming the energy of electron beam is $\sim \boldsymbol{10\ MeV}$, $\gamma \approx \boldsymbol{20}$, we have $\boldsymbol{l_0} \approx \lambda \times \boldsymbol{400} \approx \boldsymbol{248}$ Å. Assuming $\sigma_l \sim \boldsymbol{2.48}$ Å tolerance in the thickness $\boldsymbol{l_0}$ of each individual period, one has the standard relative deviation $\sigma_0 \sim \boldsymbol{1\%}$ and the coherency range $\boldsymbol{N_{coh}} \sim \boldsymbol{10^3}$, so that with the total number of periods $\boldsymbol{M} \sim \boldsymbol{10^2}$, one has a gain $\boldsymbol{G}$ only $\boldsymbol{7\%}$ below the fully-coherent $\boldsymbol{G} = \boldsymbol{10^4}$. With $\boldsymbol{M} \sim \boldsymbol{10^3}$, one has $\sim \boldsymbol{50\%}$ of the full-coherent $\boldsymbol{G} = \boldsymbol{10^6}$, which is a huge number. With the energy $\boldsymbol{5\ MeV}$, the period thickness is $\boldsymbol{l_0} \sim \boldsymbol{62}$ Å, and for $\sigma_l = \boldsymbol{1}$ Å one has $\sigma_0 = \boldsymbol{1.6\ \%}$ and $\boldsymbol{N_{coh}} \sim \boldsymbol{400}$, so that for $\boldsymbol{M} \sim \boldsymbol{100}$ one has $\boldsymbol{G} \sim \boldsymbol{0.8} \times \boldsymbol{10^4}$, (14), which is $\boldsymbol{80\ \%}$ of the fully-coherent $\boldsymbol{G} = \boldsymbol{10^4}$ and thus is a great enhancement over the fully-incoherent $\boldsymbol{G} = \boldsymbol{10^2}$. With $\boldsymbol{M} = \boldsymbol{400}$, for the same energy, we have $\boldsymbol{G} \sim\ \boldsymbol{0.8} \times \boldsymbol{10^5}$, which by more than three orders of magnitude exceeds $\boldsymbol{G_{rand}} = \boldsymbol{400}$. For the reported experiment with $\gamma \sim \boldsymbol{50}$, and $\boldsymbol{l_0} \sim \boldsymbol{1,550}$ Å, the numbers are even better.

The total standard deviation of the structure with the number of elements $\boldsymbol{M}$ and total thickness $\boldsymbol{L} = \boldsymbol{M} \cdot \boldsymbol{l_0}$, is

$$\sigma_L = \sqrt{\boldsymbol{M}}\sigma_l\ , \quad \textbf{\textit{or}} \quad \sigma_L/\boldsymbol{L} = \sigma_0/\sqrt{\boldsymbol{M}} \qquad (2.iii.3)$$

In an above example with $\boldsymbol{l_0} = \boldsymbol{248}$ Å, $\sigma_l \sim \boldsymbol{2.48}$ Å and $\boldsymbol{M} = \boldsymbol{100}$, one has $\sigma_L \sim \boldsymbol{24.8}$ Å over $\boldsymbol{L} = \boldsymbol{2.48}\ \mu\boldsymbol{m}$. Note here that the quantity σ_L is ***not*** a tolerance ***requirement***; it comes out simply as a statistical consequence of the ***only tolerance*** -- that for a single element or period, σ_l. All the above numbers show that the huge coherence gain can be achieved with the tolerances well within the existing technological standards.

At the moment, the status of experiment is as follows. A "dummy" target, which consists of two thick layers, one Mo and one Ag, was prepared to use to develop and test the entire experimental setup (accelerator beam, target, and detector). With this target, the group have made several experimental rounds on BNL ATF Linac, with the initial goal to identify the beam intensity necessary for the detector to work. At this point, we have come to the conclusion that our detector experiences unacceptably high saturation due to too high Bremsstrahlung output. This PI’s group have very recently made and estimates of Bremsstrahlung radiation and absorption for the target used for the tests. At this point, our conclusion is that the main contribution to the Brem-radiation comes from the photons with high energies, and some sort of spectral fi ltering should be build into the detector, that fi lters out all the radiation at least above $\sim \boldsymbol{100\ KeV}$, and perhaps even above $\sim \boldsymbol{50\ KeV}$.

2.iv. Radiation efficiency of water-window Cherenkov sources using atomic shell resonances for biological applications

Using the idea of large resonances of both real and imaginary part of refractive index at atomic shell resonances to attain substantial X-ray radiation by an electron beam, we applied it to ***Cherenkov*** radiation, targeting water window, that has very promising application for bio-sciences. We developed simple theory [6] of Cherenkov radiation at atomic resonances in the X-ray water window for $\boldsymbol{L}$-shells in ***K, Ca, Sc, Ti, V*** and proposed here $\boldsymbol{K}$-shell resonance in liquid nitrogen. Our results compare favorably with experiment by ***W. Knulst et al.*** [43].

The water window (WW), a soft X-ray sub-domain situated between the $\boldsymbol{K}$-shell absorption edges of Carbon ($\boldsymbol{E_C \approx 284.2\,eV}$, $\lambda_C = \boldsymbol{43.62}$Å) and Oxygen ($\boldsymbol{E_0 \approx 543.1\ eV}$, $\lambda_O = \boldsymbol{22.83}$Å), is of great importance to X-ray microscopy of live biological specimens. So far, the primarily available source of radiation in WW has been synchrotron radiation, and new alternative sources are of great interest. In a narrow vicinity of atomic shell resonances (or atomic absorption edges), a multilayer structure irradiated by relativistic electrons of moderate energy can generate strong transition radiation lines [24] centered around absorption edges, due to pronounced peaks of real part of refractive index for one of the constitutive components of the structure. In the soft X-ray domain these peaks can be large enough for the refractive index at the resonance to exceed $\boldsymbol{1}$, which in turn enables a single-layer material to radiate due to Cherenkov effect within a narrow resonant line. A recent work by W. Knulst ***et al*** [43] identified a group of elements (***K, Ca, Sc, Ti, V***) capable of exhibiting Cherenkov effect at the $\boldsymbol{L_3}$-shell atomic absorption edges within WW, and in a convincing elegant experiment demonstrated resonant radiation lines near $\boldsymbol{L_3}$ shells for ***Ti*** and ***V*** foils irradiated by ***10 MeV*** electron beam. This new source can be competitive with the existing ones.

In our research [6], we (i) added to this list another element, (liquid) Nitrogen, which is the only element in the periodic table situated between ***C*** and ***O***, and has its ***K***-shell (instead of ***L***-shells in the ***K***, ***Ca***, ***Sc***, ***Ti***, ***V***) within WW, and (ii) proposed a very simple way of evaluating the radiation efficiency, i. e. photon yield per electron, for all the candidate elements, which uses only three parameters for each element, to be easily found from published X-ray data (see, e. g. [44,45]). This simple, almost back-of-the-envelope approach yields results coinciding very closely with the experimental data [43].

When an electron passes through a medium with $\boldsymbol{n > 1}$, and its velocity, $\mathbf{v} = \beta\, \boldsymbol{c}$ exceeds the phase velocity of light $\boldsymbol{c/n(\omega)}$ at some frequency ω, $\beta \boldsymbol{n(\omega) > 1}$, an EM radiation at that frequency is emitted at the angle θ from $\vec{\mathbf{v}}$ such that $\boldsymbol{\cos(\theta) = 1/\beta n}$. The photon yield, defined as the number of generated Cherenkov photons per electron, $\boldsymbol{N_{ph}}$, can be evaluated in a transparent medium, based on [46], as

$$d^2 N_{ph}/dk\, dz = \alpha\ f_C(k)\ , \tag{2.iv.1}$$

where $\boldsymbol{k = \omega/c}$ is the radiation wavenumber, $\boldsymbol{z}$ is the propagation length, $\boldsymbol{f_C = \sin^2(\theta) = 1 - 1/\beta^2 n^2 > 0}$ is the Cherenkov factor, and $\alpha = \boldsymbol{e^2/\hbar c \approx 1/137}$ is the fine structure constant. In the X-ray domain the Cherenkov effect is rarely observable, since an necessary condition for the effect is that $\boldsymbol{Re(n) > 1}$, while the prevailing situation in the X-ray domain is that $\boldsymbol{Re(n) < 1}$. Fortunately, in the very close vicinities of those shell resonances, or the so called atomic absorption edges, very dramatic changes of both the real and imaginary parts of ε take place. When the photon energy becomes sufficient to remove electrons from a particular shell, the absorption jumps up almost discontinuously, hence the term "absorption edge". At the same time, since the newly-"unbound" electrons abruptly assume free-electron response to the radiation, the real part of ε exhibits a sharp resonance with a narrow peak; the slopes of this peak are, however, not as steep, so that the dispersion line is broader than the absorption edge. Whereas absorption edges play a major role in various application of X-rays, the

resonances of the real part of ε remains of little use to X-ray physics and applications, except for recently proposed resonant enhancement of the transition radiation in nano-multilayer solid-state structures [24], and Cherenkov radiation in WW [6,43]. Thus, in the soft X-ray domain, the real part of refractive index n (or the dielectric constant $\varepsilon = n^2$), in the very close vicinity of atomic shell resonances may ***exceed 1***, and that excess is sufficiently high (the magnitude of $\varepsilon - 1$ for the above set of lines in WW can reach ~ 10^{-2}) to allow for substantial Cherenkov radiation from electron beams of moderate energy.

Accounting for the X-ray absorption characterized by the attenuation length, $L_{at}(\omega)$, and integrating (2.iv.1) over a finite thickness of a material layer, d, along z, we have

$$\frac{dN_{ph}}{dk} = \alpha\, f_C(k)\, L_{at}(k)\, \{1 - exp[-d/L_{at}(k)]\} \qquad (2.iv.2)$$

Since in the X-ray domain we have $|n-1| \ll 1$ regardless of the sign of $n-1$, we need sufficiently high energy electrons, $\gamma^2 \gg 1$, to excite Cherenkov radiation if $n-1>0$, where $\gamma = 1/\sqrt{1-\beta^2}$ is the relativistic factor. The formula for f_C is reduced then to

$$f_C(k) \approx \Delta\varepsilon(k) - \gamma^{-2} \quad \textit{where} \quad \Delta\varepsilon = Re(\varepsilon - 1) \approx 2\, Re(n-1) \qquad (2.iv.3)$$

The spectral lines of $\Delta\varepsilon(k)$ have unfamiliar shapes, involving terms like $ln(k - k_{sh})$, $k_{sh} = c\, E_{sh}/\hbar$, E_{sh} is the absorption edge energy, and different for different shells [24,21]. In the water window, the spectral linewidths of $\Delta\varepsilon(\omega)$ are about three orders of magnitude larger than the linewidths of the respective atomic absorption edges. Indeed, a relative atomic edge linewidth, at the WW midpoint, $\lambda \sim 33$ Å, is $\Gamma \sim 0.35 \times 10^{-5}$, whereas typically, the relative linewidth, $\Delta k_{crs}/k_{sh}$ of the $\Delta\varepsilon(\omega)$ line at the crossover (see below) is $O(10^{-2})$. To estimate the maximum photon yield, we need to know, aside from the shell energy, E_{sh}, of each transition in question, three main characteristics for each of the six materials: the maximum magnitude of $\Delta\varepsilon_{mx}$ at that transition; the low-crossover linewidth, $\Delta k_{crs} = k_{sh} - k_{low}$ (or $\Delta E_{crs} = \hbar c \Delta k_{crs}$), i. e. the spacing in k-space between the lower crossover point, k_{low}, at which $\Delta\varepsilon(k) = 0$, and the absorption edge k_{sh}; and the averaged attenuation length, $\tilde{L}_{at}$, within that line below the point of atomic absorption edge, i. e. below E_{sh}. If the electron relativistic factor γ^2 and the foil layer thickness , d, sufficiently exceed $1/\Delta\varepsilon_{mx}$ and L_{at} respectively, the maximum photon yield (and the radiation spectrum) at each wavenumber does not depend on γ and d anymore, hence

$$d[N_{ph}(k)]_{mx}/dk = \alpha\, \Delta\varepsilon(k) L_{at}(k) \quad \textit{for} \quad \Delta\varepsilon(k) > 0\,, \qquad (2.iv.4)$$

and the ***total*** maximum photon yield is: $(N_{\sum})_{mx} = \alpha \int_{k_{low}}^{k_{sh}} \Delta\varepsilon(k) L_{at}(k) dk$ or

$$(N_{\sum})_{mx} \approx \alpha\, \Delta k_{crs}\, \Delta\varepsilon_{mx}\, \tilde{L}_{at}/2 \approx 1.85 \times 10^{-2}\, \Delta E_{crs}(eV)\, \Delta\varepsilon_{mx}\, \tilde{L}_{at}(\mu m) \qquad (2.iv.5)$$

The L_3-shell lines of all elements under consideration except for nitrogen are broaden due to a contribution of the nearby (higher) L_2-shell. This is, however, insignificant for our purposes, because the L_2 absorption edge is almost nonexistent, and because the fact that $\Delta\varepsilon > 0$ above the L_3-transition is almost lost for our purposes, since in that area, the radiation is strongly

inhibited by the attenuation from L_3 edge anyway). All the relevant parameters and characteristics are found in Table 1. Although nitrogen has a lower magnitude of $\Delta\varepsilon_{mx}$ at its K-transition than other materials do, its photon yield, $(N_\Sigma)_{mx}$, is of the same order of magnitude as the yield for the rest of the candidates; this is due to much longer attenuation length, L_{at}, of N.

$(N_\Sigma)_{mx}$ is the ***maximum*** yield attained at $\gamma^2 \gg 1/\Delta\varepsilon_{mx}$; less energetic e-beams engage only part of the Cherenkov line. An estimate for the yield N_Σ for any γ is as:

$$N_\Sigma/(N_\Sigma)_{mx} \approx (1-\gamma_{thr}^2/\gamma^2)^2 = [1-1/(\gamma^2\Delta\varepsilon_{mx})]^2 \qquad (2.iv.6)$$

where $\gamma_{thr} = 1/\sqrt{\Delta\varepsilon_{mx}}$ is the threshold relativistic factor to excite Cherenkov radiation; for the respective energies of e-beam, $E_{thr} = mc^2(\gamma_{thr}-1)$ see Table 1. Thus our yield estimates [6] for Ti and V at $E = 10\ MeV$ are 5.75×10^{-4} and 4.645×10^{-4} respectively, which comes much closer to the respective experimental data for V (4.3×10^{-4}) than the theoretical evaluation [21] of 1.4×10^{-4}, and within the same range from experimental data [43] for Ti (3.5×10^{-4}) as the theoretical evaluation [43] of 2.4×10^{-4}.

Table 1.

Element	**K**	**Ca**	**Sc**	**N(liquid)**	**Ti**	**V**
$\frac{E_{sh}}{\lambda_{sh}}\left(\frac{eV}{Å}\right)$	$\frac{294.6}{42.1}$	$\frac{346.2}{35.8}$	$\frac{398.7}{31.1}$	$\frac{409.9}{30.25}$	$\frac{453.8}{27.3}$	$\frac{512.1}{24.2}$
$E_{crs}\ (eV)$	12	8.9	9.3	2.1	7	7.45
$\Delta\varepsilon_{mx}\times10^3$	4.3	4.91	6.8	0.95	7	6.87
$L_{at}\ (\mu m)$	4.47	2.71	1.71	21.6	1.33	1.14
$E_{thr}\ (MeV)$	7.28	6.78	5.69	16.07	5.6	5.65
$(N_\Sigma)_{mx}\times10^3$	2.59	2.19	2.0	0.797	1.206	1.08

2.v. How short can be short? or how far we can go with pulse shortening?

A while ago, the London "Nature" has asked this PI to write an essay for their relatively new section, "Concepts", published in every second issue, with an unusual offer to write on ***any*** subject he chooses to. It should be noted that all the previous authors of that specifi c section are the most renown scientists in their fi elds, most of them Nobel Prize winners. Albeit these essays are written for more or less general scientifi c audience, their major intent is to outline beyond-the-horizon directions of the particular fi eld under the assumption that the authors have a fundamental knowledge in the fi eld and unimpeded vision of things to come. This PI has chosen to elaborate on the very notion of time as part of our living environment, and look into what is the span of time available to us, and how much and how far we can control and use it, concentrating mostly on how far we can go in generating and measuring ever shorter pulses, what is the physics beyond the various scales of time, and what are milestones on the road to ultimately short duration of time, that being Plank time, $\sim 10^{-43}\ s$. His essay has been published in Nature very recently [5].

Our Universe, according to the Big Bang theory, is about 14 billion years, or $5\times 10^{17}\ s$, old, while the ultimate time-scale ("Planck time") of the quantum cosmology, $\sim 10^{-43}\ s$, the Big Bang's birth-flash, is an elementary "grain" or "pixel" of time, within which our "regular" physics of 4-D space+time breaks down into much greater number of dimensions hypothesized by the superstring theory. Thus the time in our Universe spans within about 61 orders of magnitude.

With life-time of ~ 70 years $\sim 2\times 10^{9}\ s$, "logarithmically" speaking, we are much closer to the age of the Universe within that huge span. While the "long" end of this scale is still only of academic interest, the "short" end is becoming a hot and bustling frontier of science and technology. The best known examples are communication and computers. In the quest of higher computer performance, one of the major parameters is the clock frequency or, inversely, the clock cycle. While the UNIX computer of 1987 used to have a clock frequency around $17\ MHz$, today's off-the-shell computers have it near $3\,GHz$, or $0.3\times 10^{-9}\ s = 0.3\ ns$ (nanosecond) clock cycle.

Lasers have been moving even faster into shorter time domains. Soon after the invention of laser in 1959, the length (duration) of a pulse of light passed the ns and then picosecond ($10^{-12}\ s$) thresholds, and the race was on to shorter pulses yet. The sub-ps and femtosecond ($10^{-15}\ s$) domain became a fi eld rich of research ranging from the registration of super-fast processes, to time-resolved spectroscopy, to the characterization of semiconductors with sub-ps relaxation times, to the chemical reaction control and fs time-resolution by powerful laser pulses. The domain became also an arena for the so called Terahertz technology, which uses these pulses as e. g. a diagnostic tool to "see-through" the opaque materials and structures.

The record for shortest ***laser*** pulses at the moment stands at $4-5\ fs$, which is close to the length (~ $3\ fs$) of a cycle of near-infrared laser. The challenge is to generate controllable pulses even shorter than $1\ fs$. The reason to go shorter is that the highest spectral frequency of a sub-cycle pulse is inversely proportional to its length, τ. The photon energy is the frequency times the Planck constant, $\hbar$, so we have the pulse's highest photon energy as $E_{max}\approx \hbar/\tau$. While the sub-$ps$ and fs domains correspond to $E\sim 0.1-0.01\ eV$ typical for the molecular reactions, the domain below $0.15\ fs$ (150 attoseconds) is the atomic physics territory: it is the time for an electron at the ground state of hydrogen atom, H, to revolve around the proton; the photoionization limit of H, $\sim 13.6\ eV$, is in the upper part of the spectrum of $150\ as$ pulse. A few avenues to generate such pulses were proposed. Most recently, the sub-fs pulses have been observed experimentally [26] using high-order harmonics.

Most of these new pulses are sub-cycle or single-cycle bursts of radiation well separated from one another within long trains of them. While they have extremely broad Fourier spectrum, from radio to extreme ultraviolet domains, they differ dramatically from those generated by regular super-broad-band sources (e. g. black-body radiation): all their spectral components ideally have the same ***phase***, which is the manifestation of large-scale ***trans – spectral*** coherence never encountered in regular optics. Indeed, while super-short pulses are plentiful in the black-body radiation (e. g. sunlight), they arrive and behave completely on ***random***. The ***coherency*** and ***controllability*** make all the difference in the world of pulses.

Beyond the atomic-scale horizon, there are ions of heavy elements. In the "ionic extreme", we can think of the heaviest stable atom, uranium, with all but one electron stripped away. To remove that last electron, one needs a bit more than $\boldsymbol{110\ KeV}$ (close to the $\boldsymbol{K}$-shell transition of uranium), which makes yet shorter time scale, $\sim \boldsymbol{10^{-20}\ s}$. Beyond that, the atomic/ionic physics runs into a "quantum desert". Going still shorter, we hit the next domain of fundamental interest: quantum electrodynamic (QED), such as e. g. electron-positron pair production requiring double rest energy of electron, $\sim \boldsymbol{1\ MeV}$, and strong ***nuclear*** reactions, e. g. deuterium electro-disintegration producing proton and neutron near $\boldsymbol{1.2\ MeV}$, which are reminiscent of photoionization in atoms, but on the energy scale up to five orders of magnitude higher. The time scale respectively shrinks to ***zepto***-seconds ($\boldsymbol{10^{-21}\ s}$). The feasibility of generating and controlling sub-attosecond to ***zs*** pulses that may illuminate, time-resolve, and ultimately possibly control nuclear reaction in the future, have been discussed recently. The idea was to drive free electrons in a tight circle by a laser with the currently available intensity up to $\boldsymbol{10^{21}\ W/cm^2}$ in the "***lasetron***" configuration proposed by us within reported AFOSR grant. These electrons, to be almost instantaneously released and accelerated to the energy $\boldsymbol{E \sim 50\ MeV}$ in the massive ionization of nanoparticles of matter, should be able to generate photons in QED and nuclear domains.

Farther beyond that horizon, we enter large territory of high-energy physics, when charged particles brought to nearly the speed of light in huge accelerators, collide with target nuclei or similar counter-propagating particles to produce a cloud of new elementary particles. If we ever figure out how to ***coherently*** control the production of the same particles in these collisions, the radiation may be made much faster; a pulse with the highest photon energy of e. g. $\boldsymbol{1\ TeV}$ (million of $\boldsymbol{MeV}$'s) could ideally be $\sim \boldsymbol{10^{-27}\ s}$ short. While long way from the ultimate time scale, $\boldsymbol{10^{-43}\ s}$, this duration is still a long shot, but a worthy target to set our eyes at...

2.vi. Preliminary new research

In his research under the reported grant, this PI has started to work on a few new prospective directions, in which he and his group and collaborators has obtained promising preliminary results. These are:

- ✳ Matching elements pairs for narrow-line X-ray Transition Radiation from a Solid-State Nano-Multilayer Structure
- ✳ Fully-relativistic laser-electron gate
- ✳ Time-resolved relativistic coherent synchrotron and lasetron radiation

These new ideas have been proposed as a basis for new proposed research, which is currently actively pursued by the PI and his group under new AFOSR grant.

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